

“Hot Spots” of Submesoscale Dynamics and Their Comparison with Walleye Pollock Spawning Areas in the Pacific Waters off the Kamchatka Peninsula

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Abstract—Based on an analysis of Sentinel-1 radar images 2015–2024 covering the coastal waters off the Kamchatka Peninsula and the northern Kuril Islands, a database was compiled. The database contains 3895 manifestations of short-period internal waves and 1156 of submesoscale eddies. The analysis shows that these phenomena are a permanent and inherent components of the dynamics of regional coastal waters. The highest activity of both feature types was recorded during the summer season. Persistent areas of frequent occurrence (“hot spots”) were identified: Avacha and Kronotsky gulfs, the southeastern shelf of the Kamchatka Peninsula, and the area east of the Fourth Kuril Strait. A comparison with ichthyoplankton survey data (approximately 1500 stations for 2003–2024) reveals direct spatial overlap: areas of increased occurrence of submesoscale processes are largely confined to the main aggregation zones of walleye pollock eggs and larvae (*Gadus chalcogrammus*). This observed spatial correspondence suggests that submesoscale processes should be regarded as a previously unaccounted abiotic factor, warranting their inclusion in the assessment of ecological conditions for the reproduction of commercial resources in the region.

Keywords: submesoscale, eddy, internal waves, pollock, satellite radar imagery, Pacific Ocean

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INTRODUCTION

The waters of the Pacific Ocean adjacent to the southeastern Kamchatka Peninsula and the northern Kuril Islands are a key spawning area for one of the most productive pollock populations (*Gadus chalcogrammus*)—the East Kamchatka population [1]. Pollock spawn in this region from March to June [2]. Subsequently, larvae primarily inhabit the surface layers of the shelf zone, which are rich in plankton. This is an important adaptive mechanism providing larvae with food during the critical transition to external feeding [8]. The region’s waters are characterized by subarctic stratification. However, hydrological regimes on the shelf, continental slope, and open ocean differ [1]. The dynamics and hydrology of waters on the shelf and continental slope are formed by the combined influence of the East Kamchatka Current, which flows along the continental slope, and the tide. Tidal currents are significant in shallow shelf zones and at the shelf edge, reaching 0.4 m/s [6]. The East Kam-

chatka Current, in particular, is a source of numerous mesoscale eddy structures with a scale of approximately 100 km [5]. Smaller-scale phenomena (several kilometers)—submesoscale eddies (SMEs) [4] and short-period internal waves (SIWs) [14]—are formed at the periphery of such mesoscale eddies as well as in zones where currents interact with bottom topography. These submesoscale structures are often influenced by the tide. Both types of structures are recorded in the upper ocean layer. Due to their intense vertical velocities, SMEs serve as an effective mechanism for the vertical transport of nutrients, stimulating primary production [11]. Similarly, SIWs contribute significantly to local horizontal and vertical exchange, redistributing nutrient concentrations and creating heterogeneity in the plankton distribution [10].

Based on the analysis of incoming satellite data for the studied water area, we identified stable “hot spots”—local areas where the frequency of occurrence

of submesoscale processes significantly exceeds the background level [12–14].

In zones of high SME and SIW activity, the following mechanism of influence on the ecosystem is proposed [14]: submesoscale processes intensify vertical exchange, leading to the upwelling of nutrient-rich waters from beneath the near-surface seasonal pycnocline into the upper photic layer. This stimulates local phytoplankton blooms, creating favorable conditions for the development of zooplankton (primarily copepods)—the main food source for juvenile pollock [7]. In a particular case, in the waters near Cape Shipunsky, long-term data show a positive linear relationship between the frequency of SIW manifestations and chlorophyll-a concentrations; extreme values of both parameters coincide [14]. The northern shelf of Avacha Gulf is characterized by a parabolic dependence between the number of eddies and the chlorophyll-a concentration; a moderate number of eddies increases water productivity, while their excess leads to its decrease [13].

This influence of the SIW and SME on plankton abundance in individual “hot spots” and the relationship with the number of juvenile fish after two years [13, 14] suggests a certain role for submesoscale dynamics in the formation of the productivity of East Kamchatka pollock year-classes. However, to definitively confirm this hypothesis, further research is needed.

Although the areas of frequent occurrence of SME and SIW, as well as their intra-annual variability, have been studied in detail previously [13, 14], this study is the first to analyze these phenomena jointly and compare them with pollock spawning areas.

The purpose of this work is to identify areas of frequent submesoscale phenomena in the spawning zones of East Kamchatka pollock by summarizing long-term satellite data (surface manifestations of SME and SIW) and ichthyoplankton surveys.

METHODS

Surface manifestations of SME and SIW were recorded using radar images (RI) obtained from the Sentinel-1A and -1B satellites. C-band data in IW mode with a spatial resolution of 20 m and a swath width of 250 km were used. The satellite images were obtained from the Alaska Satellite Facility (<https://search.asf.alaska.edu/>). A total of 3491 radar images were analyzed from January 2015 to December 2024. Figure 1a demonstrates the distribution of images across the water area. The RIs were processed using the European Space Agency’s SNAP software.

We used a traditional method for visually identifying of eddies on radar images tested in studies [4, 9, 13]. Eddy structures were identified as swirling spirals (Fig. 1b); their diameters were determined by the dimensions of the ellipse circumscribing the eddy spi-

ral structure. For each manifestation, the coordinates of the center, the diameter (as the average between the major D1 and minor D2 axes of the ellipse), and the rotation type were recorded. A counterclockwise spiral was considered an eddy with cyclonic rotation (C), while a clockwise spiral was considered an eddy with anticyclonic rotation (Ac).

Surface manifestations of SIWs were recorded on radar images using the technique used in [6, 12, 14]. In the images, the waves appeared as quasi-parallel alternating (periodic) light (wavy surface — rips) and dark (smoothed surface — slicks) arcuate bands. For each surface manifestation of waves (Fig. 1c), the following characteristics were determined: leading crest coordinates, number of waves in the packet (n), leading crest length (Cr), average wavelength (λ), and propagation direction (ϕ).

To compare the spatial distribution of SME and SIW, the study area was divided into a regular grid with a 0.3° longitude and 0.18° latitude resolution. In each cell, the frequency of occurrence of submesoscale structures was calculated as the ratio of the number of recorded manifestations to the total number of radar images for the considered period. The maximum frequency of SME manifestations was 0.11, with an average of 0.02 for the area; for SIW manifestations, 0.25 and 0.04, respectively. The resulting values were normalized to these maximum values to achieve a uniform scale; thereby, an average frequency of occurrence for both types of structures across the area was about 0.2. Based on this, further analysis identified the cells where a normalized frequency of occurrence exceeded 0.4 (more than twice the average level for the water area) as “hot spots.”

The study of the spatial distribution of pollock at early stages was based on ichthyoplankton surveys conducted in the spring of 2003–2024 at a regular grid of stations (Fig. 1a). At each station, total ichthyoplankton sampling (eggs of all developmental stages and larvae) was conducted in a layer from the surface to a depth of 550 m or to the bottom using a standard IKS-80 conical net, followed by sample fixation and laboratory processing [2, 3]. The number of stations varied from year to year. The total number of stations completed over the entire period was about 1500.

For each station, average long-term values of the total number of pollock eggs were calculated. The resulting values were linearly interpolated onto a regular grid with a 0.25° latitude and longitude step. The average number of eggs per cell was 1582, with a maximum of 30 554. The egg counts in the cells were normalized to the maximum. The average normalized value was 0.05. Cells where the normalized egg number exceeded 0.1 were considered pollock spawning areas.

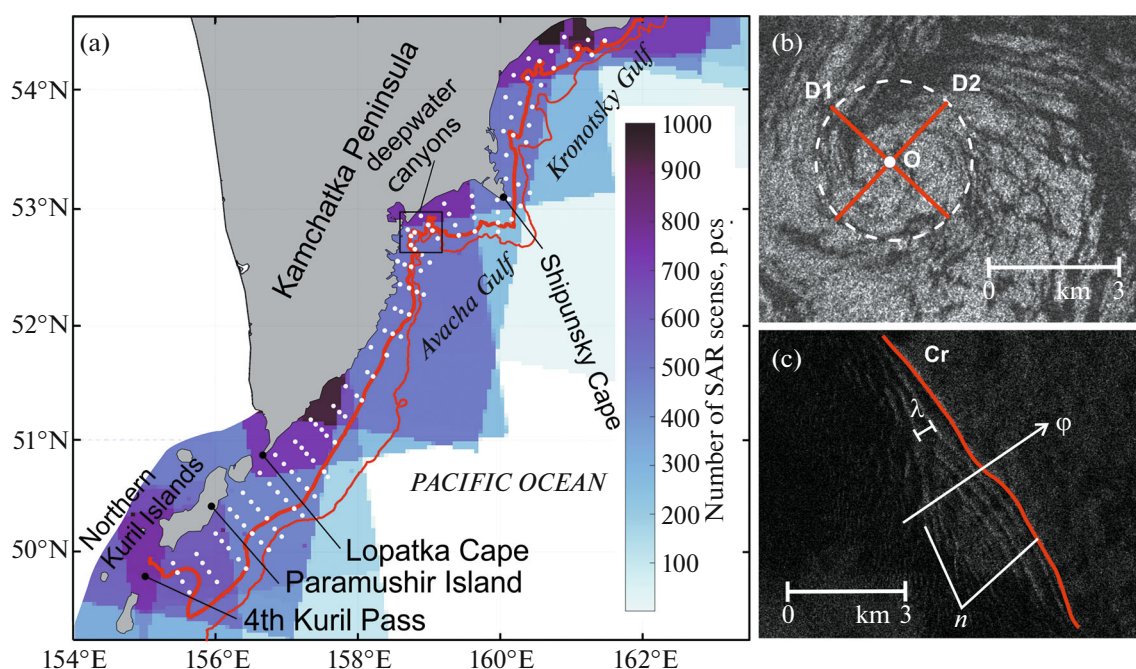


Fig. 1. The studied region and the specific features of the analysis of information on the radar: (a) the distribution of the radar images (RI) and stations of ichthyoplankton surveys (white dots) in the considered area (the red solid bold (thin) line shows the position of the 200-m (500-m) isobath); (b) the scheme of the recording the characteristics of SME surface manifestation on the radar image fragment 06/17/2018 07:23 UTC; (c) the scheme of recording the characteristics of the SIW packet surface manifestations on the radar image fragment 08/12/2024 19:32 UTC (see the designations in the text).

RESULTS

An analysis of a generalized array of satellite radar data over 10 years allowed us to create a database of characteristics of the surface manifestations of submesoscale structures and confirm their widespread occurrence in the studied Pacific Ocean area. The database includes descriptions of the characteristics of about 5000 submesoscale structures, including 1156 SME and 3895 SIW.

Despite the comparable number of radar images analyzed across seasons (from 836 to 903 images), significant differences in the frequency of occurrence and parameters of the studied phenomena were identified.

The summarized seasonal characteristics of the structures are presented in Table 1.

As the Table shows, the study region is characterized by a consistent predominance of cyclonic eddies over anticyclonic ones: in spring and summer, their ratio is (3–4) : 1. Most eddy structures have a diameter of less than 4 km. Maximum eddy activity is observed in summer, when more than half of their annual number occurs; activity is also high in spring, and declines dramatically in autumn. In winter, manifestations are extremely rare; all recorded eddies are cyclonic, and their average diameter is the greatest. The increase in eddy size during the cold season is likely due to

Table 1. Seasonal variability of characteristics of submesoscale structures according to data for 2015–2024

Characteristics/season	Winter	Spring	Summer	Autumn
Number of images	836	890	862	903
Number of Ac manifestation of SME	0	71	152	5
Number of C manifestations of SME	8	309	531	80
Total number of SME manifestations	8	380	683	85
Average diameter, km	8.1	3.5	3.7	3
Number of SIW manifestations	63	212	2243	1377
Number of waves in a packet	15	9	9	13
Average wavelength, m	440	350	370	320
Average length of the leading crest, km	43	27	27	32

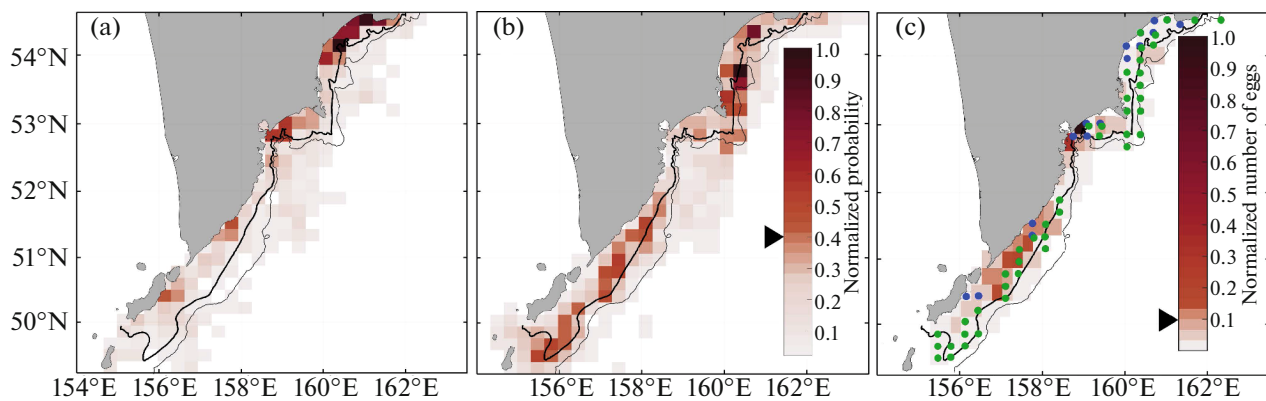


Fig. 2. Spatial distribution: (a) normalized frequency of SME occurrence; (b) normalized frequency of SIW occurrence; (c) normalized number of eggs. The blue dots show the position of the “hot spots” of SME manifestations, and the green ones show the SIW manifestations. The black solid (thin) line shows the position of the 200-m (500-m) isobath. The black triangles show the threshold for identifying “hot spots” and pollock spawning areas.

changes in water stratification and the destruction of the pycnocline. The winter minimum in activity may be partially explained by limitations of the recording method, caused by the destruction of surface films at increasing wind speeds [13].

Seasonal variability in the SIW occurrence is also clearly evident. Minimum wave activity is observed in winter and spring. This pattern is caused by the seasonal cycle of water stratification: the formation of a sharp summer surface pycnocline creates optimal conditions for the SIW generation and propagation. The highest average number of waves per packet is typical for winter and autumn, while this figure decreases in spring and summer. The wavelength and length of the leading ridge reach their maximum in winter. This is understandable because with strong winds and a quasi-homogeneous layer up to hundreds of meters in the winter months, radar images predominantly show large wave packets, while smaller structures remain indistinguishable.

The synchronous seasonal peaks of activity are most notable: the maximum manifestations of SME and SIW occur during the warm season. However, the scale of intra-annual variability varies significantly: the ratio of summer to winter occurrences is 85 : 1 for eddies and 35 : 1 for waves. In spring, numerous eddies are recorded with low wave activity. Consequently, in spring, eddy phenomena dominate among submeso-scale processes, while internal waves dominate in summer and autumn. Large eddies and long wave crests are characteristic of winter, while smaller structures predominate in summer.

The SME frequency map (Fig. 2a) shows that the majority of recorded eddy structures (approximately 70%) are concentrated in coastal and shelf zones. High frequencies were recorded in several areas of Avacha and Kronotsky gulfs, which act as the main “hot spots” of eddy activity. A lower frequency of SMEs was observed on the southeastern shelf of the

Kamchatka Peninsula and near the northern Kuril Islands (near Paramushir Island). Eddies were also repeatedly recorded in the open ocean above depths greater than 1000 m; however, their distribution density was significantly lower there. As previously identified, these patterns indicate the significant role of topographic factors and the interaction between background and tidal currents in SME generation in the region under consideration [4]. It should be noted that in the “hot spots” areas, the SME manifestations were recorded mainly at sizes comparable to the long-term annual averages indicated in Table 1.

The spatial distribution map of SIW manifestations (Fig. 2b) shows that their highest frequency of occurrence is observed over the continental slope, as well as in certain areas of the shelf. Over deep-water areas with depths greater than 2000 m, wave groups were observed primarily in Avacha Gulf and the adjacent waters to the south. The key result of the analysis is the identification of persistent “hot spots”—areas with an abnormally high frequency of SIW occurrences. The maximum frequency of waves was recorded in the waters of Kronotsky Gulf, in the area of the Shipunsky Peninsula, and south of the Fourth Kuril Strait. The location of the identified “hot spots” coincides with the results of previous studies for 2019 alone [12]. In addition to the indicated areas, increased SIW occurrence is also noted on the southeastern shelf and continental slope of the Kamchatka Peninsula and in the area east of the northern Kuril Islands. As has been recently established [14], “hot spots” in the SIW field are confined to areas of intense tidal currents over complex bottom topography (underwater canyons, sharp depth changes on the continental slope), where the energy of the internal tide is transformed into shorter internal waves. Moreover, some characteristics of the SIW (e.g., the distance between packets) corresponded to the period of the dominant tidal harmonic,

which allowed us to conclude that a significant portion of the SIWs are of tidal origin.

Figure 2c illustrates the spatial distribution of pollock eggs normalized to the maximum. Three areas of egg accumulation are clearly distinguished: the central part of Kronotsky Gulf, the waters of Avacha Gulf with local maxima in the northern shallow part of the gulf and above deep-water canyons, and, finally, the wide shelf area of the southeastern Kamchatka Peninsula with the adjacent area near the northern Kuril Islands. These areas, according to previous studies [2, 3, 8], are stable over many years and can be considered pollock spawning centers. In Fig. 2c, the dots indicate the centers of the identified areas of high eddy and wave activity (“hot spots”) according to the criteria presented above.

A comparison of the locations of East Kamchatka pollock spawning areas, where the number of eggs caught was twice the background value, with “hot spots” in the SME and SIW fields reveals the following feature. Eddies and waves are consistently observed in these areas year after year, and, as shown in Table 1, their peak activity occurs in the spring and summer seasons—that is, during the spawning and larval periods of juvenile pollock. As noted in the introduction, SME and SIW play an important role in the dynamics and hydrology of the upper sea layer, influencing the variability and redistribution of food resources. Consequently, submesoscale processes can be attributed to factors that form the abiotic environment in key areas of spawning and early-stage development of East Kamchatka pollock, which are currently not assessed in terms of environmental conditions.

CONCLUSIONS

An analysis of a ten-years archive of radar data allowed us to obtain, for the first time, statistically reliable insights into the seasonal variability of characteristics of SME and SIW and identify the areas of frequent occurrence of these features in the Pacific waters of Kamchatka and the northern Kuril Islands. The resulting database, which included 1156 SME and 3895 SIW events, revealed a consistent predominance of cyclonic eddies and distinct seasonal dynamics of both types of structures, with a maximum in summer.

It was shown that areas of increased SME and SIW occurrence in Avacha and Kronotsky gulfs, as well as on the southeastern shelf of Kamchatka, spatially coincide with key areas of early-stage development of the East Kamchatka pollock population. The peak activity of submesoscale processes occurs during the warm period of the year, partially corresponding to egg development and larval feeding.

Therefore, the results support the proposed hypothesis that the influence of SME and SIW on the upper ocean layer serves as a significant abiotic factor for pollock spawning in the study area. In areas where

they frequently occur, they can influence nutrient transport and the spatial concentration of fodder organisms [10, 11], which is important for regions of the World Ocean where fish resources are reproduced.

The revealed spatial coincidence justifies conducting specialized expeditionary research in the identified areas to quantify the influence of submesoscale processes on the survival of early-stage pollock for fishery forecasting.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

Article concept—AVZ, RAA, SEI, RDA, VAI; analysis of literature data—AOA, SEI, KAA, MAD, MDYa; writing a manuscript—AVZ, RAA, RDA, VAI, OBT; editing—AVZ, RAA, AOA, RDA, SEV, VAI, OBT, MAD; working with references and figures—AOA, SEI, KAA, MAD, MDYa.

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